MEASUREMENT OF HIGH-VOLTAGE AND RADIATION-DAMAGE LIMITATIONS TO ADVANCED SOLAR ARRAY PERFORMANCE

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SUMMARY

A description is given of the reconfigured PASP Plus experiment: its objectives, solar-array complement, and diagnostic sensors. Results from a successful spaceflight will lead to a better understanding of high–voltage and radiation–damage limitations in the operation of new-technology solar arrays.

INTRODUCTION

Before new-technology photovoltaic space-power subsystems are developed for use on operational spacecraft, increased knowledge is required in the area of space environmental effects on solar arrays. To carry out an appropriate investigation, the Geophysics Laboratory (now part of Phillips Laboratory, PL) and the Aero-Propulsion and Power Laboratory (now part of Wright Laboratory, WL), starting in 1985, decided to put together an experiment to measure the effects of the space environment on solar-array performance. The experiment was called Photovoltaic Array Space Power Plus Diagnostics, or PASP Plus for short.

The original objectives of the PASP Plus experiment were limited to the investigation of the effects of space-plasma interactions on high-voltage solar array operation at low altitudes. The Jet Propulsion Laboratory (JPL) developed a brassboard instrument capable of biasing as many as six arrays in various voltage steps up to limits of +500 V and –500 V. The JPL brassboard consisted of a digital controller, a high-voltage generation/distribution unit, four solar arrays (two planar and two concentrator designs), and various diagnostic sensors (Ref 1, 2).

In early 1990, the Space Test Program (STP) of the Air Force's Space Systems Division (SSD) offered the PASP Plus experiment a flight on a Pegastar satellite put into orbit by a Pegasus launch vehicle (both built by Orbital Sciences Corp., OSC). PASP Plus was to be part of the APEX (Advanced Photovoltaic and Electronics Experiments) mission, set up to fly PASP Plus and two small "radiation effects on electronics" experiments, CRUX and FERRO. The Spaceflight Plan for APEX was approved by Hq USAF on 3 October 1990. Because of the enhanced opportunity provided by APEX—an elliptical [350 km by 1850 km] near-polar [i = 70°] orbit with a one to three year lifetime, Phillips Laboratory (PL) and Wright Laboratory (WL) decided to broaden the scope of the PASP Plus experiment to include the investigation of the effects of space radiation dosage on long-term solar array performance. PL also decided to put on additional diagnostic instruments appropriate to PASP Plus's new scope and mission profile. When the availability of a ride for PASP Plus became known to the photovoltaic array development community, additional new-technology arrays were

offered to WL for flight on PASP Plus. PL and WL then decided to increase the number of different arrays to be flown on PASP Plus from four to eleven.

In October 1990, a meeting was held at Wright-Patterson AFB to discuss the measurements, instrumentation, and flight requirements for PASP Plus. Scientists from Phillips Laboratory, Wright Laboratory, Aerospace Corp., Naval Research Laboratory, and NASA Lewis Research Center participated. From the various discussions at this meeting, the objectives of the new PASP Plus experiment were defined.

PASP PLUS OPERATION AND INSTRUMENTATION

The objectives of the reconfigured PASP Plus experiment are:

(1) To measure the limitations in solar-array high voltage operation caused by space-plasma interactions.

(2) To quantify the long-term deterioration in the electrical performance of many different types of solar cells when exposed to the space radiation environment.

(3) To collect sufficient environmental sensor data to be able to establish cause-and-effect relationships between environmental conditions and array performance.

(4) To provide a means for "flight qualifying" various new photovoltaic technologies (new materials and/or designs).

Extensive investigations of high-voltage interactions have been carried out by groups at the NASA Lewis Research Center (LeRC), including laboratory and flight-test work (Ref. 3,4,5). Several explanations of the causes of arcing from high negative voltage operation have been given. Jongeward et al. (Ref. 6) suggest that arcing is initiated as a result of ion neutralization and associated charge buildup on a thin insulating layer over the metallic interconnects. Hastings et al. (Ref. 7) propose that arcing is due to the breakdown of gas that is emitted under electron bombardment from the coverglass on the solar cells. The arcing rate (beyond thres- hold voltage) appears to be roughly proportional to plasma density, but has a large power-law dependence on voltage level (Ref. 8). For high positive voltage operation, there is the problem of the draining of array power by electron currents flowing between the array and the surrounding space plasma (Ref. 9). The magnitude of the "leakage" current will depend on the operating voltage, plasma density, exposure of the interconnects, nature of the coverglass material (secondary electron emission), and the geometry of the sheath surrounding the array. Various computer simulations have been used to study the plasma leakage current problem (Ref. 10). Data from the PASP Plus experiment, with its many different kinds of array technology, should be very helpful in determining the relationships between various parameters.

To simulate large arrays operating at high voltage levels, we apply high bias voltages to our small arrays. Some of PASP Plus's eleven arrays will be partitioned into two or three sections, resulting in 16 elec- trically isolated, individual modules. Ten of our 16 modules will be biased. The high-voltage biasing sequences for each module (one at a time) will consist of <u>four</u> all-positive or all-negative steps (each 20 sec long) of successively greater voltage levels. The minimum difference between step values is 10 volts. Early in the APEX mission, lower bias voltages will be used, gradually increasing to higher levels after determining that the higher voltages do not disable the particular module. After satisfactorily reaching the highest voltage levels (+500 V and –500 V), a standard positive and negative data-gathering sequence [e.g., 350 V, 400 V, 450 V, 500 V] will be used to obtain detailed statistical data on array leakage (positive biases) and arcing (negative biases) as functions of bias-voltage level, array temperature, satellite altitude (ambient plasma density), and velocity-vector orientation (ram, wake, in-between).

The partitioning of some arrays will allow us to apply high-voltage biasing to only <u>part</u> of an array and not the remaining part. In some cases, we want to investigate long-term radiation damage to array perfor- mance for that part of the array <u>not</u> subjected to biasing. The high-voltage biasing, besides causing possible performance deterioration itself (detectable at the time of the bias measurements), could also increase the <u>susceptibility</u> of the biased part to later (or longer-term) contamination or radiation damage. Instrumentation included in PASP Plus will allow us to distinguish between different damage effects.

The electrical performance of each of the 16 array modules, whether biased or not, is monitored by taking numerous current-voltage measurements (I–V curves) of the module over the course of mission lifetime. The I–V curves for each module are obtained from the rapid application of dynamically varying resistance values between R = ∞ to R = 0 (corresponding to open-circuit voltage V_{OC} and short-circuit current I_{SC}) to the sun-illuminated array module. Thirty-two digitized measurements of current and voltage are recorded (all within about 2 sec) for each array module. The optimum I–V curve voltage range for an array would be from zero to just beyond V_{OC}. However, V_{OC} (and, consequently, the I–V curve) is highly dependent on array temperature, with the highest voltage levels occurring at the lowest array temperatures. Hence, we must allow for a V_{OC} corresponding to when the sun-viewing array will be coldest—coming out of eclipse into solar illumination. Temperature sensors are affixed to each array so that array performance can be correlated with temperature.

Diagnostic sensors for the PASP Plus experiment will include:

a. a sun incidence-angle sensor to measure the alignment of the arrays to the incident solar energy, especially important for concentrator arrays. To meet PASP Plus requirements, the Pegastar satellite will point its upper-deck honeycomb panel (on which any concentrator arrays will be mounted) to within 0.5° of the sun.

b. a Langmuir probe (LP) to measure low-energy plasma parameters (density and temperature). To sweep the appropriate voltage range [with respect to the space plasma], our LP will be equipped with a potential sensor (SENPOT) capable of sensing how far negative the satellite frame-ground is below space-plasma reference and compensating for this deviation. The vehicle-frame negative potential is due to the fact that Pegastar's spacecraft-power solar arrays are configured (like all space vehicles) with the positive terminal (≈ +32 V) high and the negative terminal connected to vehicle frame-ground. Because of the greater mobility of incoming electrons over incoming ions, the positive (high) end of Pegastar's arrays goes to only several volts (5 to 10) positive with respect to the space plasma while the negative end (and vehicle frame-ground) goes to 22 to 27 volts negative.

c. electrical transient sensors (E-field sensors for detection of radiated pulses and a current-loop sensor for detection of power-line pulses) connected to a transient pulse monitor (TPM) to obtain the characteristics (amplitude, rise time, integral, and pulses per time period) of arc-discharge pulses that will occur during high-voltage biasing of the arrays.

d. an electrostatic analyzer (ESA) to measure 10 eV to 30 keV electron/ion spectra and detect the passage of Pegastar through an auroral region.

e. an electron/proton radiation dosimeter to measure the short-term and long-term particle radiation that damages solar cells, leading to deterioration in array performance (as measured by the I–V curves). The design of one of the four detection domes has been altered (see Figure 1) to facilitate the measurement of 5-10 MeV protons shown to be particularly damaging to solar-cell material, especially silicon (Ref. 11); see Figure 2.
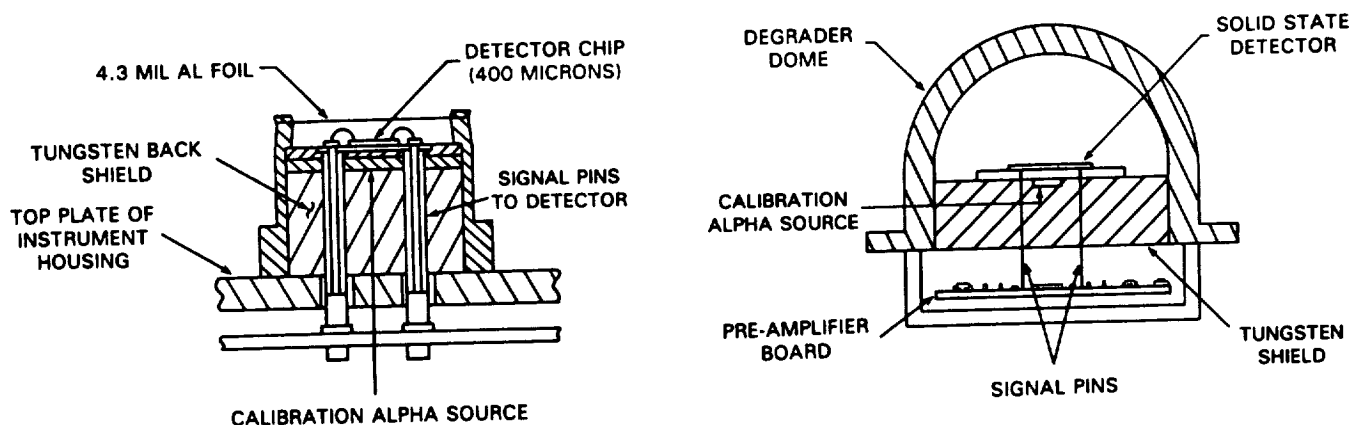

Figure 1. Domes of PASP Plus dosimeter: modified design to measure 5 - 10 MeV protons [left] and customary design for higher energy particles [right].
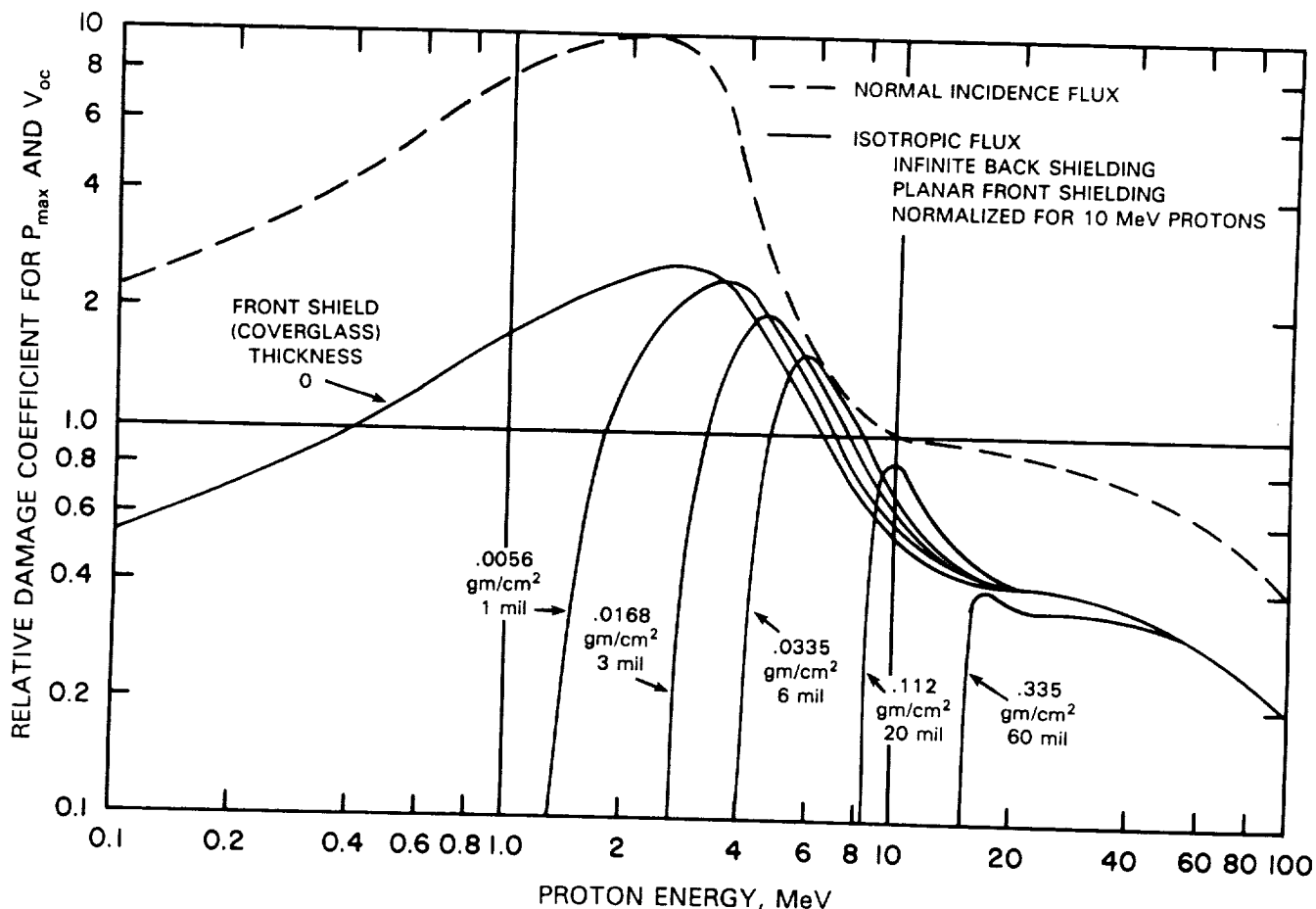
Figure 2. Relative damage coefficients for space proton irradiation of coverglass-shielded N/P silicon cells (based on P_{max} or V_{oc}).

f. a set of contamination monitors to give an indication of the amount of effluents deposited on array surfaces (this leads to decreased sunlight collection and array output power—as measured by the I–V curves). Contamination sensors will include QCMs (quartz crystal microbalances) and calorimeters. The information from these monitors will allow us to differentiate the solar-array performance degradation caused by radiation-dosage damage from that caused by contamination.

PASP PLUS SOLAR ARRAY COMPLEMENT

To maximize the utility of the PASP Plus experiment, a wide variety of conventional and advanced-concept solar cell designs will be investigated. Eleven unique solar array designs, comprising a total of 16 individual solar-cell strings (modules), will be studied on PASP Plus. The criteria used for selecting each of the solar array designs was based on electrical performance and potential for use on current and future DoD and NASA spacecraft missions. The solar array designs to be investigated on PASP Plus are shown in Table 1.

Two silicon (Si) solar cell designs will be studied. The first Si array is comprised of 2 cm × 4 cm 8-mil conventional Si solar cells laid down with conventional interconnects and coverglass. These are representative of practically all DoD and NASA solar array designs flying today (see Figure 3). The first Si array contains three electrically isolated solar-cell strings. The first of the three Si modules (strings) will not be high-voltage biased to provide a benchmark for the second and third modules that will be. The area of the third Si module

will be three times that of the second to help establish a relationship between high-voltage induced solar-cell leakage current and cell area.

The second Si solar array is comprised of 8 cm × 8 cm, 8-mil, wrap-through contact solar cells (see Figure 4). These are baselined to fly on NASA's Space Station Freedom. The wrap-through contact design is important because it reduces cell laydown manufacturing costs and increases cell survivability. This array will also be biased to determine how the cell's isolated wrap-through contact design affects its high-voltage performance.

TABLE 1. PASP PLUS SOLAR ARRAYS

ARRAY	CELL TYPE	DESCRIPTION	SIZE(in × in)	BIASED SEGMENTS
1	Si	2cmx2cm, BSF	10 × 20	2 of 3
2	Si	8cmx8cm, WTC Space Station	8 × 9.5	1 of 1
3	GaAs/Ge	4cmx4cm, 3.5-mil	10 × 20	2 of 3
4	GaAs/Ge	4cmx4cm, 7-mil	5 × 10	1 of 1
5	GaAs/Ge	4cmx4cm, 7-mil, WTC	5 × 10	1 of 1
6	GaAs/Ge	4cmx4cm, 3.5-mil, w/ICG	4 × 4.5	1 of 1
7	InP	2cmx2cm	4 × 5.5	0 of 1
8	AlGaAs/GaAs	2cmx2cm, monolithic MBG	3 × 6	0 of 1
9	GaAs/CuInSe$_2$	2cmx2cm, mech-aligned MBG	6 × 6	0 of 2
10	GaAs	SLATS Concentrator	11 × 13.5	1 of 1
11	GaAs/GaSb	Mini-Dome Fresnel Lens Concentrator, MBG	4.5 × 7.5	1 of 1

BSF = Back Surface Field
WTC = Wrap-Through Contact
MBG = Multiband Gap

Figure 3. Silicon array (#1 above) to be partitioned into three separate modules.
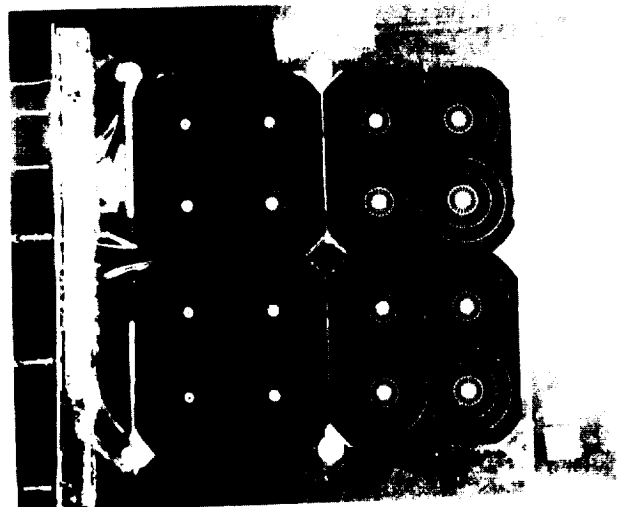

Figure 4. Si array with wrap-through contact solar cells baselined for flight on NASA's Space Station Freedom.

All of the next four solar array designs shown in Table 1 utilize GaAs on Ge solar cells, but all differ in electrical and/or mechanical configuration. The GaAs/Ge solar cell represents a very important technology because GaAs offers better energy conversion, radiation resistance, and high temperature performance over Si solar cells.

The first of the four GaAs/Ge arrays is comprised of 4 cm x 4 cm, 3.5-mil GaAs/Ge solar cells. This array is similar to the first Si array in that it has three separate electrical strings laid down with conventional interconnects and coverglass. The first module (string) will not be biased to provide a control for the second and third high-voltage biased modules. Also, the area of the third module will be twice that of the second module to help establish a relationship between cell leakage current and cell area.

The second GaAs/Ge array consists of one string of 4 cm x 4 cm, 7-mil GaAs/Ge solar cells laid down with conventional interconnects and coverglass. This array will be biased and compared in high-voltage perfor-mance with the third GaAs/Ge array, which will consist of 4 cm x 4 cm, 7-mil GaAs/Ge solar cells with wrap-through contacts. The second and third GaAs/Ge arrays will be identical in all respects (solar cell material, cell area, array substrate, and mounting and wiring design) except for the conventional top-bottom versus wrap-through contact design differences. The fourth GaAs/Ge array will consist of one string of 4 cm x 4 cm, 3.5-mil GaAs/Ge solar cells coated with an alumina/silicate based CVD-deposited coverglass. The glass coating will conformally cover the entire area of the array, including interconnects and cell edges, with the intent of providing conductor to space plasma isolation resulting in improved high-voltage performance.

The seventh, eighth, and ninth arrays shown in Table 1 (InP, GaAs/ CuInSe$_2$, and AlGaAs/GaAs cell designs, respectively) will not be high-voltage biased, but their performance will be measured as a function of exposure to the natural space environment and orbital temperature excursions. The cell size for each of these three designs will be 2 cm x 2 cm, and all strings will be laid down with conventional interconnects and coverglass. The InP solar cell is important because of its high conversion efficiency and extremely high radiation resistance. The GaAs/CuInSe$_2$ solar cell is a dual-junction mechanically stacked design which offers high conversion efficiency and extremely high radiation resistance to electrons. The AlGaAs/GaAs cell design is important because it is dual-junction and monolithic and promises to yield very high conversion efficiencies.

The last two PASP Plus solar arrays shown in Table 1 are concentrator designs. The first is the survivable low-aperture trough system (SLATS) concentrator array which collects and focuses (concentrates) light onto GaAs solar cells using trough-shaped (venetian blind like) metal mirrors. The solar cells are mounted to the backside of the mirrors and are illuminated by the mirrors to which they are adjacent. This design is important for enhancing the survivability of the solar array against man-made threats (e.g., high-powered lasers) and the natural space environment, as well as having the capability to operate at higher voltages. This capability arises from the fact that the solar cells are effectively shielded from the space plasma environment. The second concentrator is the mini-dome fresnel-lens GaAs/GaSb design which promises extremely high conversion efficiencies through the use of its dual-junction mechanically stacked GaAs and GaSb solar cells and prismatic coverglass. This design is important not only for its high conversion efficiency, but for its potential use in operating at higher voltages. In this design, the GaAs/GaSb solar cells are isolated from the space plasma environment by the concentrator elements and the array support structure.

CHARACTERISTICS OF PEGASTAR SATELLITE

PASP Plus will be integrated onto a Pegastar satellite bus and placed into orbit by a Pegasus launch vehicle. With the enhanced capability afforded by the Pegasus/Pegastar system, an elliptical (350 km x 1850 km) near-polar (70° inclination) orbit was made available to satisfy PASP Plus's objectives. The launch will take place from a B-52 aircraft in the Western Test Range off the coast of California (see Figure 5). Both the Pegastar satellite and Pegasus are being designed and built by Orbital Sciences Corporation (OSC) as a low-cost DoD alternative for small payload missions. The first Pegasus launch from a B-52 was successfully completed in April 1990. PASP Plus is scheduled for the fourth Pegasus launch in November 1992.

Figure 5. The Pegasus launch vehicle accelerating into orbit after being released by the B-52.

PASP PLUS TEST ARRAYS
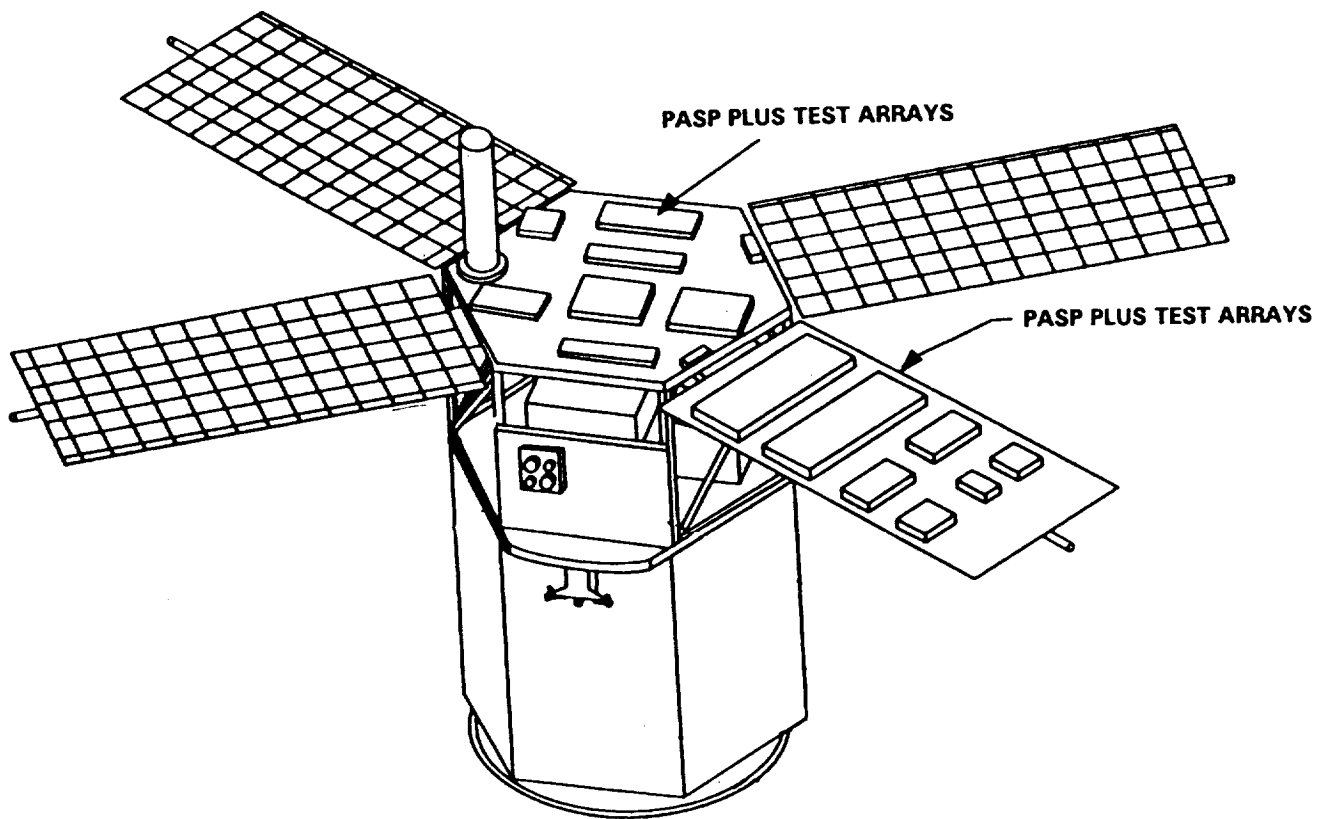
PASP PLUS TEST ARRAYS

Figure 6. The Pegastar satellite bus showing the general location of the PASP Plus test arrays.

The Pegastar satellite with integrated PASP Plus experiment is shown in Figure 6. The satellite bus will measure approximately 60 inches in height and 44 inches in diameter. Power for PASP Plus and other satellite subsystems is provided by three 60 in x 22 in solar array panels producing between 320 and 380 watts of power for up to three years on orbit. Total weight to orbit of the Pegastar vehicle including PASP Plus is approximately 820 pounds. The Pegastar satellite will be three-axis stabilized and oriented so the PASP Plus test arrays will be continuously sun-pointing to within ±0.5 degrees. The PASP Plus test arrays are mounted on a combination of the hexagonally shaped upper shelf and one deployable panel (see Figure 6). PASP Plus electronic subsystems are mounted on the lower avionics payload shelf.

The dosimeter and ESA each have special pointing requirements. The dosimeter domes will view a direction parallel to the ecliptic plane and normal to the sun-satellite line. This will provide the optimum look direction for the dosimeter throughout the orbit while minimizing the time facing the earth. The ESA apertures will view a direction normal to the ecliptic plane and 90° from the dosimeter's pointing direction. This will orient the ESA so as to look along the earth's magnetic field lines when the vehicle is in the auroral regions.

Most of the high-voltage plasma interactions objectives of PASP Plus will be achieved while the vehicle is near perigee passing through the ionospheric F—region and/or through auroral regions. Most of the radiation degradation objectives of PASP Plus will be achieved while the vehicle is near apogee in the equatorial regions (Pegastar's line of apsides will rotate ~1.5° a day in its orbital plane). During the 1–3 year lifetime of the APEX mission, measurable radiation-induced degradation will be seen in the performance of the PASP Plus test arrays. An orbit maintenance capability might be provided on Pegastar to enable it to remain at high apogee for the duration of the mission or possibly the initial apogee would be increased. This will assure the continued high-altitude radiation exposure necessary to satisfy PASP Plus objectives.

The PASP Plus solar arrays will be tested and assembled as a completed subsystem at WL. Diagnostic instruments and electronics equipment will be tested and calibrated at PL's Geophysics Directorate (GP). The completed PASP Plus system (arrays and electronics) will be environmentally tested at PL/GP and delivered to OSC for integration onto the Pegastar satellite bus. PASP Plus delivery to OSC is planned for April 1992. The completed Pegastar system will be shipped to Edwards AFB, CA in October 1992 for integration onto the Pegasus launch vehicle at NASA's Dryden Research Center. PASP Plus data will be collected in both a real-time mode and recorded play-back mode. Continuous 24-hour operation of the experiment is planned for the mission lifetime.

EXPECTED RESULTS FROM A SUCCESSFUL FLIGHT

Achievement of PASP Plus's experimental goals is highly dependent on maintaining the proper orientation (sun pointing) and achieving the proper orbit for the Pegastar satellite.

Pegastar's sun-pointing accuracy of ±0.5° is obviously essential for the concentrator arrays (e.g., the SLATS power generation decreases significantly beyond 0.5° and drastically beyond 1.5°). However, even for the planar arrays, in an experiment where the interaction effects may be small and/or slowly developing and where we wish to distinguish one effect from another (e.g., radiation vs. contamination degradation), it is important to minimize any undesired variation in sun illumination that would cause even small changes in array I–V curves.

APEX's nominal 350 km (190 naut mi) perigee will provide the maximum electron density (in the order of 10^5 to 10^6 cm^{-3}) in the region around perigee and allow investigation of space-plasma induced effects over the largest useful range of electron density variations. After six months of flight, a very large data base on arc-pulse parameters (negative biasing) and plasma-leakage current parameters (positive biasing) as functions of bias levels and types of array will be collected over the flight achievable ranges of the controlling parameters: array temperatures, plasma density (perigee through apogee), auroral passage, and velocity-vector orientation. This large data base will permit examination of the correlations between all the linkable variables and lead to the establishment of cause-and-effect relationships for high-voltage space-environment interaction effects.

These relationships will then be available for analytic study, modeling, and code development. The information on array operating voltage limitations developed through analysis of PASP Plus results can be used to decide on the choice of operating voltage levels for particular kinds of arrays in various orbital regimes.

APEX's nominal 1850 km (1000 naut mi) apogee will allow passage of Pegastar through the lower portion of the inner radiation belt only when apogee occurs near equatorial geomagnetic latitudes. The line of apsides (the perigee–apogee line in the orbital plane) continuously rotates about 1.5° per day throughout the mission. On a long-term basis, Pegastar's apogee will pass through the radiation belt at equatorial latitudes only a small fraction (about one-quarter) of the rotation period. A higher apogee (up to 2000 or 2200 km) would significantly increase the dosage (or lessen the time to reach a specific dose accumulation), but there are limitations in the Pegastar-Pegasus boosting capability.

With some modest improvement in apogee, we expect to obtain sufficient radiation dosage in one year to see array performance degradation (as measured by the I-V curves) in Si cells in the order of 8 to 12 percent. For the more rad-hard materials (GaAs and especially InP) and the concentrators, the degradation may be only a few percent. If Pegastar's apogee is limited to 1850 km, we may need two or three years to see radiation-induced degradation to these levels. Information from the contamination sensors (QCMs and calorimeters) will be used to separate contamination effects from radiation effects. The radiation-induced performance degradation data for all the PASP Plus test arrays will be correlated with the radiation dosage data gathered from our electron/ proton dosimeter to try to establish cause-and-effect relationships. A section of the PASP Plus dosimeter has been designed to measure 5–10 MeV proton radiation, an important source of solar cell degradation. The information on radiation-damage limitations developed through analysis of PASP Plus results can be used to decide on the choice of solar-cell material or array configuration for operation in particular orbital regimes.

Within the first year after a successful PASP Plus flight, correlated PASP Plus data would be made available to the space-power communities in DoD and NASA. PL and WL, working closely with NASA LeRC, will conduct a series of workshops which will be targeted to major topics of interest such as high-voltage operation and EMI-generation effects. As data on array performance degradation from radiation effects becomes available (1½–3 years, depending on flight apogee), additional workshops will be held on radiation effects on new cell technologies and concentrator arrays. Results from these workshops will be directed towards upgrading relevant space-power design guidelines and test standards.

CONCLUSIONS

PASP Plus's complement of solar arrays and diagnostic sensors and APEX's mission profile provide us with a unique opportunity to investigate both the high-voltage and the radiation-damage limitations to advanced solar array performance. Full utilization of the results of the PASP Plus experiment should be made by space systems developers before fielding future space-power subsystems that might be subjected to unwanted environmental interactions. Failure to determine the extent of interactions problems by experiments such as PASP Plus could lead to serious flaws in future space-power subsystems.

REFERENCES

1. Guidice, D.A., "Photovoltaic Array Space Power Plus Diagnostics Experiment", Third Annual Workshop on Space Operations, Automation and Robotics (SOAR '89), NASA Conf. Publ. 3059, 1990, pp. 515–519.

2. Burger, D.R., Photovoltaic Array Space Power Plus Diagnostics Experiment, PL-TR-91-2002, 1990, pp. 12–42.

3. Snyder, D.B., "Discharges on a Negatively Biased Solar Cell Array in a Charged-Particle Environment", Spacecraft Environmental Interactions Technology - 1983, NASA CP-2359, AFGL-TR-85-0018, 1985, pp. 379-388.

4. Grier, N.T., "Plasma Interaction Experiment II (PIX II): Laboratory and Flight Results", Spacecraft Environmental Interactions Technology - 1983, NASA CP-2359, AFGL-TR-85-0018, 1985, pp. 333-348.

5. Ferguson, D.C., "The Voltage Threshold for Arcing Solar Cells in LEO—Flight and Ground Test Results", AIAA 86-0362, AIAA 24th Aerospace Sciences Meeting, Reno, Nevada, Jan. 6-8, 1986.

6. Jongeward, G.A., Katz, I., Mandell, M.J., and Parkes, D.E., "The Role of Unneutralized Surface Ions in Negative Potential Arcing", IEEE Trans. Nucl. Sci., Vol. NS-32, No. 2, 1985, pp. 4087–4091.

7. Hastings, D.E., Weyl, G., and Kaufman, D.,"Threshold Voltage for Arcing on Negatively Biased Solar Arrays", J. of Spacecraft and Rockets, Vol. 27, No. 5, 1990, pp. 539–544.

8. Ferguson, D.C., "Solar Array Arcing in Plasmas", Third Annual Workshop on Space Operations, Automation and Robotics (SOAR '89), NASA Conf. Publ. 3059, 1990, pp. 509-513.

9. Mandell, M.J., Katz, I., Steen, P.G., Schnuelle, G.W., "The Effect of Solar Array Voltage Patterns on Plasma Power Losses", IEEE Trans. Nucl. Sci., Vol. NS-27, No. 6, 1980, pp. 1797-1800.

10. Thiemann, H., and Schunk, R.W., "Particle-in-Cell Simulations of Sheath Formation Around Biased Interconnectors in a Low-Earth-Orbit Plasma", J. of Spacecraft and Rockets, Vol. 27, No. 5, 1990, pp. 554–562.

11. Tada, H.Y., and Carter, J.R., Solar Cell Radiation Handbook, JPL Publ. 77-56, 1977, Chap. 4.